EUV Sources for Metrology: Experience and R&D Portfolio

Authors

R. Lebert[a], T. Mißalla[a], C. Phiesel[a], B. Jägle[a], A. Farahzadi[a], W. Diete[a] , K. Bergmann[b], T. Wilhein[c]

a) Bruker ASC GmbH, Bergisch Gladbach, Germany
b) Fraunhofer Institute for Laser Technology, Aachen, Germany
c) Institute for X-Optics, RheinAhrCampus, Remagen, Germany

Introduction

EUV sources for metrology are a keystone for supporting the infrastructure of EUVL when developing and ramping up the technology, production or processes. Within Bruker ASC and with our research partners there is long experience in developing and producing such sources, such that we can provide a portfolio of matched solutions based on both technologies discharge produced and laser produced.

Starting at AIXUV in 2000 with commercializing discharge based EUV-sources for metrology – our EUV-Lamp – we meanwhile have produced and delivered about 20 of these systems.

At our partner Fraunhofer Institute for Lasertechnics, prototype sources are operated which drive x-ray microscopes and interference lithography exposures and deliver up to 40 W/(2 p sr) of inband EUV. In brightness optimised operation modes > 20 W/mm²/sr have been demonstrated; Parameters of independent measurements allow seeing > 30 W/mm²/sr as feasible.

When source brightness is the issue, laser produced (LPP) sources are advantageous. Members of our group are working since 1997 on and with LPP EUV sources. Emission Spectra of frozen Xenon and of tin have been published before 1999. LPP are used in our spectrophotometer (CEUVS) and in an EUV microscope. Intense research and use of EUV-LPP sources is ongoing at our research partners at RAC, Remagen, LZH, Hannover and FhG-ILT, Aachen.

History

Work on EUV sources for metrology has been started in 1997 at the RWTH Aachen and the Fraunhofer Institute for Lasertechnics. It has been continued since there, at AIXUV / Bruker for metrology sources and at Philips / Xtreme for HVM source.
From the very beginning, we have considered and investigated DPP and LPP approach.

JOURNAL OF APPLIED PHYSICS VOLUME 83, NUMBER 9 1 MAY 1998

Narrowband laser produced extreme ultraviolet sources adapted to silicon/molybdenum multilayer optics

G. Schriever,[a] K. Bergmann, and R. Lebert
Lehrstuhl für Lasertechnik, RWTH Aachen, Steinbachstr. 15, 52074 Aachen, Germany

(Received 28 May 1997; accepted for publication 21 January 1998)

The extreme ultraviolet radiation emitted from a plasma generated by a pulsed Nd:yttrium aluminium garnet laser is investigated around 13 nm wavelength for several low Z elements (lithium, nitrogen, oxygen, fluorine). A narrowband EUV source can be designed by using the narrowband line emission of low Z elements in combination with the broadband reflection characteristic of silicon/molybdenum (Si/Mo) multilayer mirrors. Experimental results are discussed within a theoretical model, which allows a deduction of an optimization criterion for a maximum conversion efficiency. The Lyman-α line of hydrogenlike lithium ions fulfills the demands for high intense, free-standing narrowband emission at the long wavelength side of the silicon absorption L edge.
© *1998 American Institute of Physics*. [S0021-8979(98)00900-8]

I. INTRODUCTION

Radiation in the extreme ultraviolet (EUV) region is of great interest for the future technology of producing and analyzing structures on the nanometer scale. Besides synchrotron radiation sources, table top EUV sources like laser produced plasmas are under investigation for laboratory applications. Intense laser radiation creates a hot dense plasma by interaction with the surface of a target. These plasmas emit radiation in the EUV wavelength region. To adapt the spectral distribution of the radiation of laser produced plasmas to Si/Mo multilayer optics, appropriate target material has to be selected. High conversion efficiency can be reached by adsorption of the laser parameters.

Plasmas of high Z elements emit radiation with a continuous spectral distribution. They are under investigation for EUV projection lithography[1–3] because of the high conversion efficiency for broadband radiation.[4,5] Several analytical applications, however, require narrowband radiation. This can be generated by broadband radiation in combination with monochromators. An alternative is the coarse filtering of an emission line of low Z element plasma. The number of electron transitions in these highly ionized atoms is low and the emitted spectral lines of these plasmas are well separated.[6]

Especially, chemical analysis of structured surfaces can be done by (near) resolved x-ray photoelectron spectroscopy (XPS) using EUV radiation. For high energy resolution of this method a narrowband EUV source is needed. For high lateral resolution the radiation has to be focused to a small spot onto the surface of a sample, for example, by multilayer mirrors. Furthermore, pulsed radiation enables a time-of-flight (TOF) detection of the generated electrons. Using TOF, an image of the electron energy spectrum can be obtained over a wide spectral range.[7]

Si/Mo multilayer mirrors consist of a stack of alternating thin films of silicon and molybdenum. The period thickness is adapted to the wavelength and the incidence angle of the radiation by Bragg's law.[8] High reflectivity is reached for radiation at the long wavelength side near to the silicon absorption L edge at $\lambda = 12.4$ nm. $E_{ph} = 100.6$ eV, respectively. These mirrors reflect a wavelength band of about 0.5 nm width depending on the number of periods.[9,10] In combination with an emitter of few standing lines a multilayer mirror makes monochromators dispensable.

For EUV technology in general and especially XPS requirements, the combination of laser produced plasmas as pulsed, highly intense EUV sources and Si/Mo multilayer mirrors as efficient reflectors is well suited.

II. TARGET SELECTION

The photon energy of the emitted radiation depends on the target element, the ionization state, and the electron transition. The ionization state and population of the shells are determined by the plasma temperature and density, which can be tuned by the laser parameters intensity, wavelength, and pulse duration.

Figure 1 shows the dependence of the atomic number of the element and the electron transition on the photon energy of the emitted radiation. The photon energy region around the silicon absorption L edge at 100.6 eV is enlarged. We only consider inner shell transitions between shells with quantum numbers $n < 4$, because their population in the thermal equilibrium is higher compared to shells with higher quantum numbers.[10]

On the low energy side of the silicon absorption L edge within an energy range from 80 to 100 eV the transitions of hydrogenlike lithium and nitrogen and lithiumlike oxygen and fluorine can be identified (Table I). The emission lines of the lithiumlike ions are split by the different J transitions into a doublet. The transition energies of heliumlike beryllium ($Z = 4$) and higher Z elements are on the short wavelength side of the silicon L edge where the absorption of silicon is high.[11] For this reason the radiation is not suited for Si/Mo multilayer application. However, it might be of interest for reflection with rhodium/beryllium multilayer mirrors.

JOURNAL DE PHYSIQUE IV
Colloque C1, supplément au Journal de Physique III, Volume 7, janvier 1997

A gas discharged based radiation source for EUV-lithography

R. Lebert *, K. Bergmann *, G. Schriever * and W. Neff **

* Lehrstuhl für Lasertechnik, RWTH Aachen, Steinbachstraße 15, D-52074 Aachen, Germany

** Fraunhofer-Institut für Lasertechnik, Steinbachstraße 15, D-52074 Aachen, Germany

A new high repetitive, compact and low cost gas discharge based EUV „lamp" has been studied as an alternative to laser-produced plasmas as EUV sources. First results using oxygen in a fast discharge of electrically stored energy around 1 J lead to a conversion efficiency of about 0.1 % for the emission at 13.0 nm which is suited for the use with Mo/Si-multilayer mirrors. Using Xenon a broadband emission in the investigated wavelength range from 10 nm to 18 nm is observed. With a first version a source with 40 W electrical input power could be demonstrated that emits about 50 mW/(4πsr) around 13 nm at a repetition rate of 150 Hz. No debris and no electrode erosion was observed after more than 10^7 pulses done up to now. Making use of the remaining optimisation potential this concept seems to be promising to fulfil the requirements of extreme-ultraviolet lithography

1 INTRODUCTION

Extreme-ultraviolet (EUV) lithography used for the future generation of semiconductor devices requires compact radiation sources around a wavelength of 13 nm, which emit up to 20 W in a bandwidth of 2 eV [1]. Up to now the main interest has been devoted to laser-produced plasmas as EUV sources [2-4]. Using such sources in combination with multilayer mirrors the production of structures around 100 nm has been successfully demonstrated [5,6]. However, there are still problems in achieving the required average radiation power. These problems are mainly in reducing the debris of the plasma source and in standing by the high power laser systems. In this work a new kind of gas discharge based EUV source is presented where the problems of reproducibility, operation at a sufficient high repetition rate and the limited lifetime known from other gas discharge based EUV sources, e.g., the capillary discharge [7] or Z-pinches have been solved. In comparison to laser-produced plasma sources the gas discharge plasmas offer the advantages of a higher wall plug efficiency for the EUV radiation, lower apparative effort and a reduced debris problem.

The principle of the radiation source presented in this paper is similar to a small Z-pinch or a gas filled capillary discharge. However, the special design of the electrodes allow for a repetitive operation and a long lifetime due to low electrode erosion. In contrast to the other concepts a switch is omitted which leads to a better coupling of the electrical energy to the discharge plasma and a lower apparative effort.

2 EXPERIMENTAL SET-UP

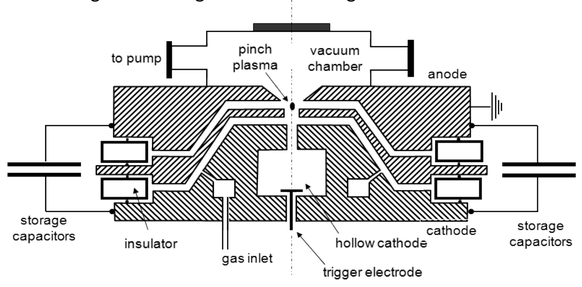
The pinch plasma is created by a fast discharge of a charged capacitor. This discharge leads to a pulsed current with a rise time in the range of about 100 ns and peak values in the range of several kiloampere. The current compresses and heats the neutral gas to a plasma with an electron density in the range of 10^{18} cm^{-3} and a temperature of several 10 eV which is appropriate to achieve emission around 13 nm.

The electrically stored energy per pulse is in the range of only a few Joule. A low inductive design of the electrical connections and the omitting of a switch allows to achieve the required current amplitudes with such low storage energies and ensures an optimal conversion of the electrical energy to the plasma.

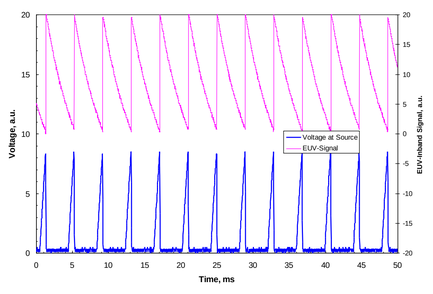
The special design of the electrodes lead to a low erosive and highly repetitive mode of operation as will be shown below. The typical dimension of such

DPP Sources

With some experience, a DPP source for metrology is most simple:
Build electrodes which concentrate discharge to a desired location; apply high voltage and fill in gas until a high current discharge occurs.



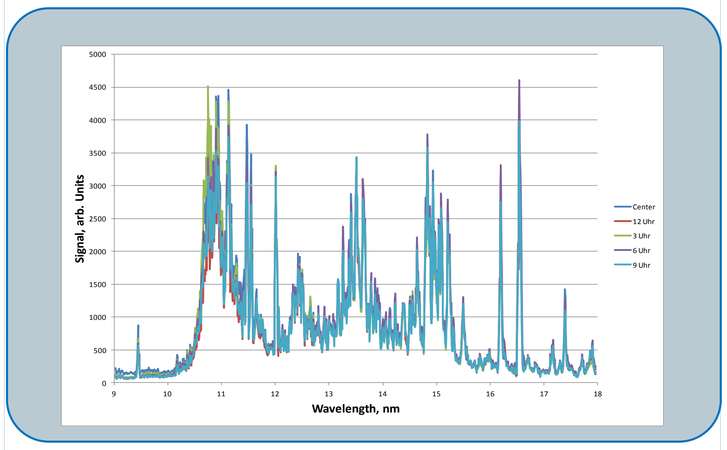
Schematic of electrode system in EUV-Lamp



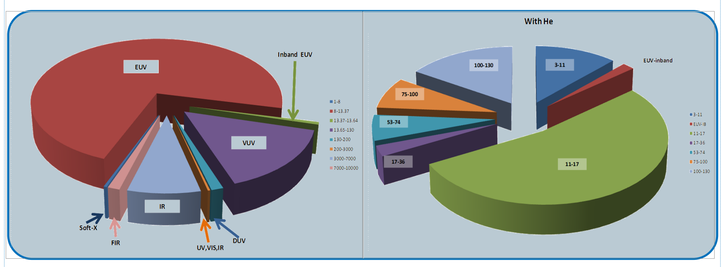
Voltage and EUV signals from repetititive discharge in EUV-Lamp

DPP Sources

With currents of some kA discharged a plasma of > 30 eV is generated in the spark, such that the working gas emits a spectrum of highly ionized atoms.
Hence, the selection of the working gas allows for tuning the spectral distribution; e.g. narrowband line emitters and broadband emission can be generated with the same EV lamp system by just using another working gas.



Isotropy of emission spectrum of Xenon from EUV-Lamp under different angles



Quantified distribution of emission over spectral channels as measured at EUV-Lamp.

This basic concept is supplied by BASC in various configurations. Our standard product for metrology is the EUV-Lamp operated with Xenon, which may be supplemented with OEM or customer specific interfaces or features.
Together with our partners, we can supply solutions for shorter wavelengths and higher power

Stand-alone automatic EUV-Lamp System

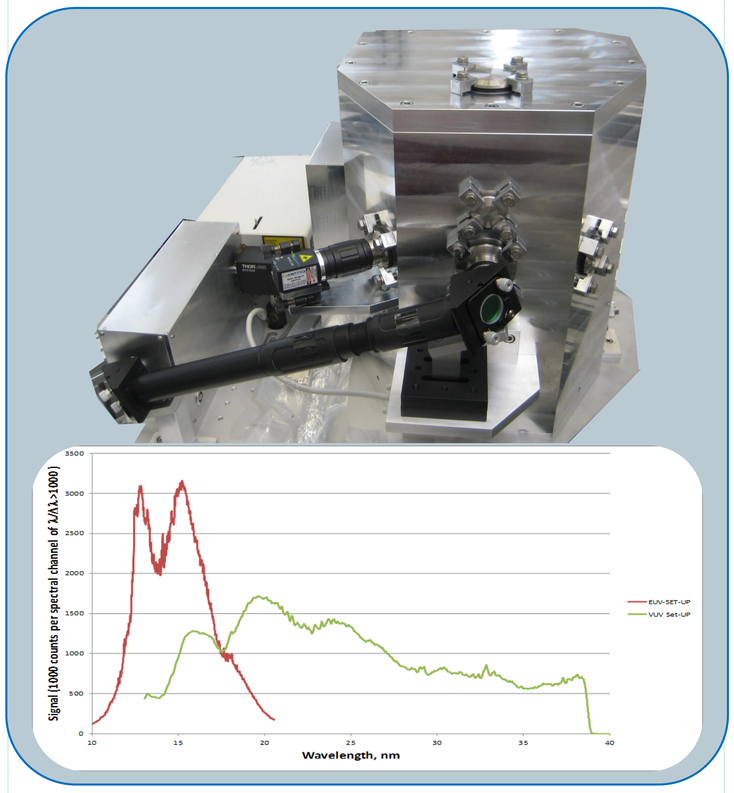
The typical EUV-Lamp delivers up to 750 mW/(2 π sr) of inband EUV (> 8 W/(2 π sr) of total EUV). About 500 Mpulses of electrode life (= 2*MTBF) delivers 3 months to one year of 8 hour per day emission. Most of the EUV-Lamps, which we have produced are specially interfaced or directly integrated into tool solutions. The lamps have been and are being used in EUV-Reflectometers, EUV resist exposers, EUV-microscopes, EUV-scatterometer, for metrology tool calibration, for optics qualification and as sources for spectrograph calibration.

For higher powers as e.g. required for exposing resist for patterning, we collaborate with the Fraunhofer ILT in developing sources of higher powers.

EUV-Lamp Platform prototype for up to 40 W EUV inband source from FhG-ILT

LPP Sources

LPP metrology sources are an alternative for spectroscopic metrology. The broadband spectrum of gold offers good coverage of the whole spectral range from soft-x (down to 2 nm if necessary) to the VUV (> 40 nm). For our CEUVS spectrophotometer, we used LPP source with gold target supplied by LZH. Operating this source with 200 mW laser power is sufficient to obtain good spectroscopic results on sample reflection or transmission within less than one minute of exposure.

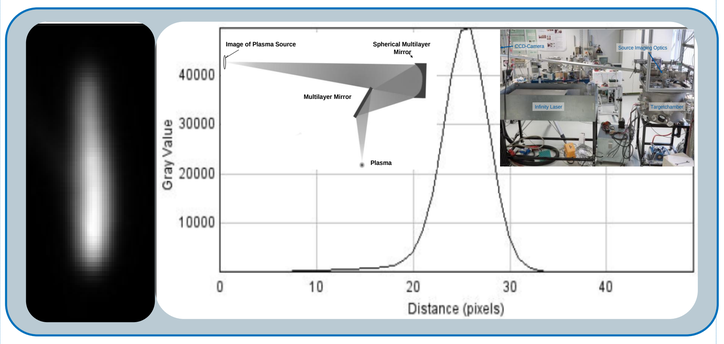


LPP source and emission spectrum as supplied from our partner LzH for spectrophotometer

LPP source for brightness

Whenever brightness and small imaged fields are required, LPP sources are advantageous.

For this purpose we made concept studies on small spot high brightness sources.
We performed experiments with an experimental laser operated with up to 10 kHz ,using only 2 – 3 mJ per pulse. On a pool of liquid Sn80Pb20 tin, lead alloy optimized CE of 1.85 % inband were achieved with 150 ps pulses. Source sizes of < 20 µm and better than 5 µm position stability have been measured.
We are confident to realize a straight forward path to supply > 100 Wmm²/sr of EUV inband radiation even on extended areas with largely commercial components.



9 times magnified inband EUV-Image of source and horizontal profile on CCD with 20 µm pixel.
Schema of set-up and in RAC-Lab as insert.

Conclusions

With our EUV and XUV sources, both types: discharge produced and laser produced, we have the option to select the best suited source for any application. Our own portfolio is supplemented by sources available at our research partners, e.g. Fraunhofer, Laserzentrum Hannover, Rhein-Ahr Campus Remagen, MBI.

In summary we can cover narrow and broadband emission spectra, power levels of up to 40 W of EUV-inband radiation, brightness exceeding 200 W/mm²/sr; source sizes from 20 µm to 1 mm in diameter and lifetimes up to years.
But what is also of importance is that we can also apply the most economical solution for any given application; such as our EUV-Lamp, or a < 5 mW in 2 p sr EUV inband LPP source.

With our design experience in systems for synchrotron and in realizing stand alone tools in UHV , integration and mechanical and vacuum quality is straight forward. s

Acknowledgments: Thanks to the BMBF for funding within the project "13 N10572: "EUV mask" in the consortium "EUV Lithographie für den 22nm Knoten".

E-Mail presenting author: rainer.lebert@bruker-asc.com